SUSPENDED SEDIMENT SUPPLY DOMINATED BY CHANNEL PROCESSES IN A LOW-GRADIENT AGRICULTURAL WATERSHED, WILDCAT SLOUGH, FISHER, IL, USA

BY

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THESIS

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ABSTRACT

Nutrient loading in rivers in the Upper Sangamon River Basin has led to concentrations of nitrate that exceed EPA water quality standards and concentrations of phosphorous that promote algal growth. Nitrogen and phosphorous are primarily introduced by fertilization and transported via leaching through the soil profile and adsorption to fine sediments, respectively. This study estimates the relative contribution of suspended sediment from various land use types entering into the Wildcat Slough, a low gradient, intensively managed 61.3 km^2 watershed in the Upper Sangamon River Basin in central Illinois, USA. The land is primarily used for agriculture, but forests, floodplains, banks, a restored prairie and grasslands, and a pasture are also present in the watershed. The majority of the river is retained within a deep, channelized ditch with a network of drainage tiles emptying into it as it flows through the farm fields. In the lowermost reaches, however, it is allowed to freely meander and has established point bars and outer banks.

The relative contributions of sediment from each land type are estimated using geochemical fingerprinting. A suite of tracers showing significant variances between the different land types within the Wildcat's watershed is statistically verified to distinguish between sources. An unmixing model uses the concentrations of these tracers from samples collected in suspension and from the different land types to estimate the fraction of the suspended load derived from each source. Sources adjacent to the meandering reaches, including banks, floodplains, and forests contribute significant fractions of the suspended load. During storm events, very little suspended sediment is derived from agricultural uplands, indicating a disconnection of the uplands from the channel, possibly due to the low relief of the uplands and the dominance of tile drainage in routing water to the channel.

These findings indicate that management practices should focus on limiting sediment supply from near channel areas in meandering reaches to minimize the input of nutrients adsorbed to the sediment. Best practices may include installation of a buffer between a meandering channel and fertilized or farmed land, or requiring a minimum distance that fertilizer can be applied near channel banks. These practices would ensure that nutrients do not enter the river through natural channel migration.

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INTRODUCTION

Recent acknowledgment of the environmental significance of fine sediment, and the role that land use change towards intensive row-crop agriculture has on fine sediment fluxes, has motivated identification of the sources of suspended river sediments to enable better management practices. Awareness of the negative impact large suspended sediment loads in rivers are having on the environment is growing (Correll, 1998, Warren et al., 2003, Sidorchuk and Golosov, 2003). Because of the inverse relationship that exists between grain size and surface area, the largest concentrations of nutrients and contaminants are on the finest sediments (He and Walling, 1996). Nutrients, such as nitrogen and phosphorous, adsorb to fine sediments and enter the waterways, leading to concentrations that surpass US Environmental Protection Agency water quality standards (Owens and Walling, 2002). When human-induced land changes increase the suspended load, the negative effects can vary from eutrophication (Correll, 1998) and toxicity (Warren et al., 2003), to excessive sedimentation in lakes and reservoirs, or floodplains and channels (Sidorchuk and Golosov, 2003).

Before European settlement, central Illinois was covered by thick prairie grasses and wetlands in the uplands, while forests filled the valleys and floodplains (Transeau, 1935). Conversion from prairie and wetlands to pasture and intensive row-crop agriculture throughout much of the Midwest began during the mid to late 1800s to make use of the fertile soil and support the growing population (Bogue, 1951). This conversion involved installing subsurface drains, initially made of clay and therefore often referred to as “tiles”, to drain water into the channels and intentionally lower the water table (Beauchamp, 1987). Rivers were also straightened, extended headward, and emplaced in artificial channels with deeper and wider dimensions than were naturally present. These modifications altered channel network and watershed hydraulics (Rhoads and Herricks, 1996), while allowing for the replacement of native vegetation in favor of intensive agriculture.

Changes to land use and channel morphology impacted how water and sediment were transported within the Upper Mississippi Valley (Knox, 2001). In the uplands, bare soil was exposed where thick vegetation previously dominated. A reduction in the amount of vegetation cover led to a general rise in surface runoff and a reduction in infiltration (Morin and Benyamini, 1977), causing an increased water yield when combined with the efficient routing of water by drainage tiles (Bosch and Hewlett, 1982). As a result, large watersheds (>100,000 km^2 [38,610 mi^2]) experienced more frequent overbanks flows (Knox, 2001), and floodplain sedimentation rates were 1 to 2 orders of magnitude higher than typical pre-settlement values (Miller et al., 1993). Conversely, smaller watersheds (<500 km^2 [193 mi^2]) have experienced reductions in flood magnitudes and subsequent floodplain sedimentation (Knox, 2001). Within the channels, changes in stream power and sediment transport capacity from channelization prompted sedimentological responses leading to unintended morphological adjustments, including point bar formation and outer bank erosion within channelized reaches (Brookes, 1998).

Hydrologic and geomorphologic reactions to land use changes in the Midwest have an impact on environmental conditions within larger watersheds such as the Mississippi River Basin (David et al., 2010), but less is known about how first order watersheds respond to intensive management. Due to the spatial and temporal differences in erosion that become magnified by the flashy and episodic nature of sediment transport in small watersheds (Walling and Webb, 1987), assessing the influence of individual sediment sources can be difficult. For example, a frequently tilled agricultural field with row crops may have a higher erosion rate and lower infiltration rate than a highly vegetated forest (Vidon et al., 2010), due in part to the effect of raindrop impact in areas of loose, unvegetated soil (Loch, 2000). With a reduced infiltration rate, sheet erosion is generally the most common form of sediment transport in a farm field, but it is not uncommon for rill-interrill erosion to contribute significantly on a tilled field (Foster, 1986). In contrast, the dominant process in a floodplain may be headcut or channel bank erosion.

Although differences in erosion across a watershed are well documented, how they manifest themselves in low gradient, intensively managed watersheds like those found ubiquitously in central Illinois, is less certain. Currently, it is unclear whether spatial variations in land management result in different rates of sediment supply because the lack of relief may not provide enough energy to even initiate transport. It is also uncertain what role, if any, channel morphology plays in transporting sediment within the channel and on the floodplain in these low gradient environments. This study quantifies the relative contributions of six different land use types (row-crop agriculture, banks, forests, grasslands, a pasture, and floodplain) to the suspended sediment load of a low gradient, first order watershed and examines the relationship between channel morphology and suspended sediment flux.

MATERIALS AND METHODS

Study Site. The Wildcat Slough is an alluvial stream located in Fisher, Illinois ~20 km (12.4 mi) northwest of the University of Illinois at Urbana-Champaign (Figure 1). It is a first order tributary to the Sangamon River within Champaign County. The average annual precipitation in the county from 1981-2010 was 1051mm/yr (41.4 in/yr) with the highest rain totals occurring in the summer months. Typically, the hottest month is July and the coldest is January, with highs of 29.4°C (84.9°F) and 0.5°C (32.9°F), and lows of 18.3°C (64.9°F) and -8.3°C (17.1°F), respectively (ISWS, 1981-2010). A drought in the summer months (July-September) of 2013 resulted in below average amounts of precipitation. Precipitation for each month was 1.6 cm (0.6 in) or more below the monthly averages since 1981 (ISWS, 2013).

The primary plants that are grown for agriculture within the Wildcat's watershed are corn and soybean. In 2013, corn began sprouting in late May-early June and was harvested in late October-early November.

The 21.3 km (13.2 mi) long river has a 0.49% gradient and occupies a 61.3 km^2 (23.7 mi^2) drainage basin with a 0.81% gradient. Apart from the final 2.0 km (1.2 mi) reach before it flows into the Sangamon River, the Wildcat is channelized (Figure 2A). The channel has been widened, straightened, and deepened. In contrast, the downstream reach freely meanders and has active point bars and cut banks, migrating ripples, and large woody debris that create large pools (Figure 2B).

To characterize the different land uses, photographs of the Wildcat Slough watershed were obtained from the Illinois State Geological Survey geospatial data clearinghouse (ISGS, 2013). A map of the watershed using 2004 NAIP Orthophoto Quarter Quadrangles for Champaign and Ford counties was made in ArcMap10.1 in PCS NAD1983 UTM Zone 16N

(Figure 1). Different land uses were digitized by combining aerial photography with observed boundaries of land usage in the sampling area.

The land surrounding the channelized reach of the Wildcat Slough is used for agriculture, whereas land usage adjacent to the downstream meandering section varies. Land types in the watershed include active channel banks, forests, intensive row-crop agriculture, grassland/prairie, pasture, and floodplain (Figure 1; Table 1). Forests are present in both the floodplain and riparian corridors surrounding the river. These corridors act to buffer the channel from farm runoff in areas where agricultural fields are close to the meandering river. In the pasture, the cattle are allowed to roam freely, sometimes crossing the channel. When they do, the cows destabilize the bed and banks, and mobilize sediment. Cattle are less frequently found walking within the forested floodplain and crossing the channel there, as well. Other areas of the meandering reach lack bank stability where vegetation is not present. The banks of the channelized reach differ because they are heavily vegetated. At certain times of the year the channel bed in the channelized reach will also be vegetated, which is much different from the meandering reach containing mobile bedforms.

Channel Change Analysis. Historical photographs of the Wildcat Slough watershed dating back to 1940 were georectified in ArcGIS using the 2004 NAIP Orthophoto Quarter Quadrangles for reference to assess the location and amount of channel change (Figure 3). The georectification process consisted of finding common ground control points between the 2004 NAIP image and the un-rectified photos. The most commonly used points were hard structures such as road intersections that were very unlikely to move between subsequent photos. To track channel change over time, channel center lines were digitized in ArcGIS for photographs from 1940, 1955, 1974, 1988, 1998, and 2004, and a buffer as wide as the channel was added.

Sediment Fingerprinting. To calculate the relative contribution of each land use to the suspended sediment load transported by the Wildcat Slough, the land uses need to first be distinguished from each other. Sediment fingerprinting offers many advantages for this because it can be applied to a variety of watershed sizes (Olley and Caitcheon, 2000; Song et al., 2003; Rhoton et al., 2006; Mukundan et al., 2010) and between different watersheds (Collins et al., 1998; Walling, 2005). Many different properties have been used as sediment fingerprints, including major and trace element concentrations (Collins et al., 1998; Walling, 2005), magnetic susceptibility (Yu and Oldfield, 1989; Slattery et al., 1995), clay mineralogy (Gingele and De Deckker, 2005), particle size analysis (Walling and Amos, 1999), radionuclide concentrations (Walling and Amos, 1999; Walling, 2005), organic matter content (Collins et al., 1998; Walling and Amos, 1999; Papanicolaou et al., 2003; Walling, 2005), and stable isotope geochemistry (Papanicolaou et al., 2003; Fox and Papanicolaou, 2008). While some techniques use tracers whose concentrations are independent of local geology (eg. radionuclide concentrations), others may be distinct to specific sites based on their mineralogy or particle size. Given that it is unlikely for a single property to be capable of distinguishing between source materials, composite fingerprints based on combinations of trace and heavy metal geochemistry has proved to be very useful (e.g. Rhoton et al., 2006; Walling, 2005; Collins et al., 1998). Using a combination of tracers creates a composite fingerprint. The composite fingerprint is the optimum combination of individual tracers that have been statistically verified to distinguish between all potential sources.

In the Wildcat Slough watershed, the composite fingerprint distinguishes land uses based on differences in soil type and vegetation. Since organic matter, heavy elements, and trace elements vary greatly between soil types and vegetation types (Walling, 2005), these were targeted as potential components of a composite fingerprint for use in the Wildcat Slough.

Source sampling. Sampling of sediments from land sources was done at monthly intervals to reflect the chemical and isotopic changes of the soil throughout the farming season. In total, 55 source samples were taken from March through November, 2013. At least one sample was taken from each of the different land types within the Wildcat Slough watershed per month from March to November, 2013. Samples were collected on the same day suspended sediment collection was initiated so that the two types of samples could be compared. Source sediments were collected from locations showing active erosion where possible, such as rills or the outer banks of a meander, to ensure that the sediments contributing to the suspended load were the same as that collected. Each sample was extracted from the ground using a trowel to remove the top 10 cm (3.9 in). Between sites, the trowel was wiped clean to avoid contamination.

Two samples were collected from each location, with one sample used for heavy and trace metal analysis, and the other one used for organic analysis. Samples for metal concentration analysis were placed directly into a labeled polyethylene plastic resin bag. Samples for organic analysis were first wrapped in aluminum foil and then placed in a labeled polyethylene plastic resin bag.

Source samples were taken to the lab and dried at 60°C (140°F). They were then crushed with mortar and pestle and sieved to retain the <63μm (2.4×10^{-3} in) portion. To avoid contamination, lab equipment was cleaned between samples. First, the excess sediment was brushed away. Then, the surfaces of the mortar, pestle, and sieves were wiped with deionized water, followed by methanol, and again with deionized water. They were either left to air dry or wiped dry with a low-lint paper laboratory wipe. This ensured that there was no residual organic or metal material.

Suspended sediment sampling. Suspended sediment samples were collected by an *in situ* sampler during storm events (Figure 4, Phillips et al., 2000). The 1m (3.28 ft) long PVC tube sits at 0.6 of the mean flow depth and preferentially collects the sediment in suspension. Abrupt changes in cross-sectional area between the small inlet tube and the bigger PVC tube cause the sediment to settle out before flowing out the other end (refer to Phillips et al., 2000 for specific dimensions and equipment used). It was installed before each of six storm events and left out until the falling limb of the hydrograph flattened to baseline. The trap was secured to two fence posts and filled with native water before installation. When the sampler was retrieved, the contents inside were emptied into a 5-gallon bucket and brought back to the lab. Between May and November, 2013, suspended sediment samples were collected during six rain events (Table 2). Because of the summer drought, many suspended sediment samples did not yield enough sediment for full analysis of all the geochemical properties.

Upon returning from the field, the 5-gallon bucket filled with the suspended sediment sample was immediately stored at 4°C (39.2°F) until the sediment had settled (~ 1 week). The majority of the water could then be scooped out of the bucket using clean mason jars. This continued until the bottom sediment began to re-suspend. The last few centimeters of water were removed by filtering through a 47 mm (1.8 in) diameter, 0.45 μm (1.8×10^{-7} in) pore-size, hydrophilic PTFE membrane filter under a hand-powered vacuum at 16.9-33.9 kPa (5-10 Hg). The filters were immediately dried at 60°C (140°F) to separate the sediment from the filter. After all of the water was removed, the remaining sediment could be scooped out with a lab spoon. Once empty, the 5-gallon bucket was rinsed and scrubbed with water. Between storm events the filter holder, receiver, and funnel were cleaned according to the USGS procedure (Shelton, 1994).

Chemical Analyses. For metal concentration analysis, 1 g (0.04 oz) of sediment was weighed and placed in an 8mL (0.3 oz) glass vile and sent to Activation laboratories in Ontario, Canada. These samples underwent trace element geochemistry analysis on an ICP/OES after aqua regia digestion. This leaching procedure involved soaking in a solution of three parts HCl to one part HNO_3 at 95°C to dissolve most oxides, many silicates, including trace-element rich micas and clays, all sulfides and carbonates, and many organic substances. Material remaining after aqua regia digestion is mostly quartz and other phases that tend to contain little of most trace elements. The other sediment samples were analyzed for $\delta^{13}C$, $\delta^{15}N$, and C/N, and required 30±2 mg (1×10^{-3} oz ± 7×10^{-5}). Samples were wrapped in tin capsules for analysis on a Costech 4010 elemental analyzer in series with a Delta V Isotope Ratio Mass Spectrometer by the DeLucia Lab at the Institute of Genomic Biology at the University of Illinois, Urbana-Champaign. The results of the stable organic isotopes are provided in delta notation. Delta notation refers to the difference between the isotopic ratio of the sample and an interlaboratory standard, and is expressed, using $\delta^{13}C$ in this example, as

$$\delta^{13}C = \left(\frac{(\frac{^{13}C}{^{12}C})_{sample}}{(\frac{^{13}C}{^{12}C})_{standard}} - 1 \right) \times 1000‰ \qquad (1)$$

The value is expressed in units of per mil (‰) or parts per thousand deviation from the standard. The $\delta^{13}C$ standard is VPDB, the $\delta^{15}N$ standard is air. The standard used for percent C and N was acetanilide.

Fingerprint Development and Unmixing Model. Results of the bulk geochemistry and C and N isotope analyses were input into a two-step statistical model to identify a fingerprint capable of distinguishing between sediment sources. First, each chemical property measured was analyzed individually, using the Kruskal-Wallis H test to determine which properties could differentiate between source sediments. Each property scoring above the critical value for the H test is a potential tracer because it differs significantly between the different sources. The potential tracers were combined through discriminant function analysis to determine the optimal combination of tracers capable of identifying between the individual sources, known as the composite fingerprint (based on Walling, 2005; Collins et al., 1998). The fingerprint was determined based on the minimization of Wilks' lambda using a stepwise function (Collins et al., 1998). A low Wilks' lambda corresponds to the addition of a new tracer to the fingerprint which improves the variability between the properties of each source, whereas a high Wilks' lambda is associated with tracers of equal concentration among sources and thus no ability to distinguish between sources. The composite fingerprint capable of confidently differentiating between the farms, forests, grassland, floodplain, pasture, and banks will therefore have a low Wilks' lambda value. Each time the discriminant function added a new tracer to the composite fingerprint, it increased the probability that the fingerprint could discriminate between sources by maximizing the variability between source tracer values (i.e. decreasing Wilks' lambda).

The composite fingerprint was incorporated into an unmixing model to calculate the relative contribution each source made to the suspended load in each sample. The goal of the model was to minimize the difference between the observed composition of the suspended sediment and a linear combination of the fingerprints of the sources. To ensure equal weighting of each tracer, the tracers were normalized by subtracting the minimum measured value from the sources and dividing by the range of measured values to produce normalized tracer concentrations between zero and one for all source samples. When multiple samples exist for a particular source, the normalized concentrations of tracers were averaged to produce an average composite fingerprint for that source.

The unmixing model is a forward model which calculates the misfit between a linear combination of the source fingerprints and the observed suspended sediment fingerprint. The model begins by generating a list of all possible combinations of the six sources which add to 100% in 5% increments. For each possible combination of sources the misfit between the combined composite fingerprint and the measured fingerprint is defined as the sum of the square of the difference between the model and measurement for each tracer. The best model is chosen as the one which minimizes this error. Sensitivity of the model to variability between the individual source measurements made was assessed by dropping individual source measurements in turn and repeating the unmixing model. If the best fit solution remains quantitatively similar despite subsampling of the source samples, then the choice of the best fitting model is not dominated by a single sample.

XRD Analysis. Samples from the forest, floodplain, farm, and pasture were analyzed for their mineralogy to help explain the variability in heavy and trace concentrations between each source. Analysis of the samples was carried out at the Illinois State Geological Survey using X-ray diffraction (XRD). The preparation and analysis were completed following previously developed methods (Glass and Killey, 1986; Hughes and Warren, 1989; and Hughes et al., 1994). Oriented clay mineral samples were analyzed with a Scintag® XDS2000 with a theta/theta goniometer and Copper K-alpha radiation. Step-scanned data was collected from 2° to 34° 2θ with a fixed time of 5 seconds per 0.05° 2θ for each sample. All resulting traces were analyzed using Jade 9+®, the semi-quantitative data reduction software from Materials Data Inc. (MDI).

RESULTS AND DISCUSSION

Field Area. Sample locations are given on a digitized land use map of the Wildcat Slough watershed and a close up of the sampling area is provided (Figure 1B and C). Sample locations were all along the lower 3.4 km (2.1 mi) of the river, and include channel reaches that are channelized and some that are meandering, and contain many different land uses (Figure 1C). Land within the drainage basin is used almost entirely for intensive row-crop agriculture (60.8 km^2 [23.5 mi^2], 99.1%), but other land uses are present (Figure 1C; Table 1).

Changes in channel traces of the Wildcat Slough over the time period from 1940 to 2004 show the most common locations for channel migration (Figure 3). Note that all of the channel change is focused in the downstream meandering section and that the upstream channelized section was channelized prior to the first set of photographs in 1940. Between 1940 and 2004, the total length of the channel decreased 0.6 km (0.4 mi, -2.3%).

Distinguishing properties of the sources. Samples were collected from the Ashkum silty clay loam, Elliott silty clay loam, Martinsville silt loam, Ozaukee silt loam, Penfield, loam, and Sawmill silty clay loam (Figure 5; Table 3). Farm field samples were collected from the Ashkum silty clay loam, Penfield loam, Ozuakee silt loam, and the Elliott silty clay loam. Clay content in the A horizon for these four series is typically less than 20% (USDA-NRCS, 2013). Organic matter (O.M.) ranges from 1-5% (USDA-NRCS, 2013). The Official Soil Descriptions (OSDs) for these series state that weakly cemented iron-manganese concretions are common below the A horizon (USDA-NRCS, 2013). Grassland samples were collected from the Martinsville silt loam. The A horizon contains 5-20% clay minerals and a high sand content. Organic matter content is moderately low. Floodplain, pasture, forest, and some bank samples were collected from the Sawmill silty clay loam. In this soil, O.M. ranges from 4.5-7% in the A horizon and iron-manganese concretions are also present in the A and B horizons (USDA-NRCS, 2013).

The chemical concentrations identified as potential tracers based on the Kruskal-Wallis *H* test show clear distinctions between the sources (Table 3). Farm field samples have the lowest average values for magnesium, manganese, and total carbon. Grassland samples have the highest concentrations of total carbon and nitrogen, and $\delta^{13}C$ values indicate that they are more enriched in ^{12}C, relative to ^{13}C, than most other sources. The only exceptions to this are forest samples, which are equally enriched in ^{12}C, but can be distinguished from grassland samples by their high manganese concentrations. Conversely, bank samples contain the least amount of ^{12}C in relation to ^{13}C. Bank samples also have the highest concentration of magnesium, but the lowest phosphorous and total nitrogen content. The highest values of phosphorous are found in the pasture. Floodplain samples are generally similar to bank samples in that they have low total nitrogen and phosphorous, and high magnesium concentrations, however, they contain much more ^{12}C.

Floodplain samples are most easily distinguished from the other sources by the XRD analysis (Figure 6). Relative to the total clay content, the floodplain contains the least amount of illite and smectite, but the highest proportion of kaolinite and chlorite (Table 4). But for kaolinite, all of these mineral families contain magnesium.

Stability of source composition in time. Source samples were collected from May to November, 2013 to reflect any seasonal variations in their geochemistry. Kruskal-Wallis *H* tests were conducted for each geochemical property to determine if there were significant changes in concentration over time. The results of this analysis showed that the geochemistry of the soil did not change significantly throughout the sampling season. Thus, source samples collected throughout the year can be compared to suspended sediment samples from every event.

Geochemical analysis. The geochemical composition of the suspended sediment is proportional to the relative amount of sediment each source contributes to the suspended load and the geochemistry of each source. Figures 7-12 graphically display the concentrations of select tracers for individual sources. The graphs for farm (Figure 7), floodplain (Figure 8), and pasture (Figure 9) show little to no overlap between the source samples and the suspended sediment samples. In contrast, the forest (Figure 10), bank (Figure 11), and grassland (Figure 12) source samples do overlap with all three suspended sediment samples. From these observations, the suspended sediment exhibits similarities to the forest, bank, and grassland sources while appearing to have no influence from the other sources. This rough visual analysis of the results provides an initial qualitative determination of which sources contribute to the suspended load.

Creating the fingerprint. In step one of the two-step statistical procedure, all individual tracer properties were tested for their ability to distinguish between sources in the Kruskal-Wallis H test (Table 5). Higher H values show a greater ability to distinguish each source. The critical H value, with 95% significance, was 11.07. Of the 26 potential tracers, 18 were able to differentiate between the six sources. These 18 tracers were then run in step two of the fingerprint procedure. The resulting composite fingerprint, which maximizes the variability between the six sources, was %N, Mn, Mg, $\delta^{13}C$, and P. This fingerprint is capable of assigning 100% of the source samples to their respective true source types and proficiently discriminates between potential sources (Table 6).

Although suspended sediment samples were collected throughout the sampling period (Table 2), they were not all used in the final analysis for calculating the relative contribution of each source. Only samples FPSS-1, 2, and 3, which were collected during storm events from May 15-22, were used in the analysis. This is due to the fact that concentrations of trace metals from samples FPSS-6 and 7 exceeded those from the source samples. Since the suspended sediment's geochemistry is a product of the concentrations of its sources and the relative proportion that each source contributes, this result indicates the presence of unidentified sources such as in-stream bars or plant life, or variability within the land-use types that were not measured.

Outliers from bank and grassland samples were also identified based on major differences in their chemical compositions. These samples are FPPr-1 and McBank-5 (Table 3). Subsequent statistical analyses are presented without inclusion of these source samples and suspended sediment samples FPSS-6 and 7.

Unmixing model. The unmixing model, using the five tracers from the discriminant function, provided estimates of relative source contributions. These source contribution estimates were similar between each suspended sediment sample. The results indicate that ~50% of the suspended sediment leaving the Wildcat Slough watershed is derived from the banks, while the forests and grasslands contribute the rest (Table 7). Although all three samples indicate contributions from the forest, grassland, and banks, the result for FPSS-1 shows significantly less contribution from the forest and much more from the grassland. Since select suspended samples were removed from the analysis, we accounted for potential contributions from an unidentified source in the suspended sediment samples used in the analysis by considering the end-member situation of the unused suspended sediment samples composed entirely of sediment from this unidentified source, and thus, representing this source. In other words, the geochemical compositions for the unused suspended sediments are equal to an unidentified seventh source. By running the unmixing model with these samples as a seventh source, we determined that it could only contribute a maximum of 5% to the suspended load.

Interpreting the sediment sources. Connecting the historical channel change analysis with the results of the unmixing model suggests that upland sources do not significantly contribute sediment to the channel, and only sources near the meandering reach of the river add to the suspended load. While the unmixing model does not specify whether forest, grassland, and bank contributions are from the meandering reach or the channelized uplands, having inputs from only the meandering section is consistent with the channel change analysis and unmixing model result showing no contribution from the farms, which are found only in the uplands. This conclusion raises the question as to whether land use, channel character, or relief is the main control of sediment supply.

Connecting hydraulic principles with the channel change analysis suggests that suspended load contributions from the banks of the Wildcat Slough are limited to the outer banks of the meandering reach, and not the channelized reach. In a typical meandering river, like the downstream section of the Wildcat Slough, the highest rates of bank erosion are at the outer banks of river bends due to velocity differences and secondary flow vortices which maximize shear stresses at these locations (Kikkawa et al., 1976). Comparatively, straightened and channelized reaches, like the upstream section of the Wildcat, lack channel bedforms and bends that localize erosion. Furthermore, the banks of the channelized reach are heavily vegetated (Figure 2A), and would require greater shear stress to induce erosion than would the unvegetated banks of the meandering reach. Additional bank contributions likely come from localized portions of the meandering reach that are used for cattle crossing.

Past channel migration observed to occur within the meandering reaches has been focused mostly within the forested, pastured, and grassy areas (Figure 3). While there are small patches of grassland in the uplands near the channelized reach (Figure 1), and some forested riparian buffers also exist, it seems less likely that these locations contribute to the suspended load than the areas of similar land usage within and adjacent to the floodplain of the migrating channel. This is due in part to observed channel migration only through forest and grassland areas in the meandering section (Figure 3), and also to the lack of sediment input from other upland land types adjacent to the channelized reach of the Wildcat Slough. Table 7 shows that farms, which are located exclusively in the uplands surrounding the channelized reach, do not contribute to the sediment load of the Wildcat. If this finding is consistent for all upland sediment sources, then it suggests that sediment transport from the uplands directly to the channel has been obstructed. It is possible that channelization and installation of unnatural levees at the top of channelized banks has impeded direct sediment transport to the channel, the lack of relief in the uplands prevents substantial surface runoff and overland transport, or that tile drains in the subsurface limit substantial overland flow.

Comparison to other representative watersheds in the Midwest. Results from the Wildcat Slough watershed can be compared with the South Amana sub-watershed in the Clear Creek watershed of Iowa because both are representative of land use, soil type, and climate in the Midwest. However, the South Amana sub-watershed differs significantly from the Wildcat Slough's average gradient of 0.81%, in that average hillslope relief is 4%, and ranges from 1-10%. During the early stages of storm events, upland soils dominate the suspended load because fine, loose particles are easily entrained by overland flow on steep slopes (Wilson et al., 2012). After the "first flush" of sediment, and during subsequent storms, the suspended load is comprised of mostly in-channel sediments because upland sources have been exhausted. In the South Amana sub-watershed, relief has a significant impact on particle entrainment in the uplands. For the same reasoning, relief in the Wildcat Slough watershed has a significant impact on preventing particle entrainment in the uplands.

The Driftless Zone of northwest Illinois and southwest Wisconsin is also a potentially representative region for land usage in the Midwest, but it has uncharacteristically higher relief compared to surrounding areas which experienced repeated glaciations. In response to land use change, uplands in the Driftless Zone experienced widespread soil erosion, leading to floodplain deposition in excess of 1 m (3.3 ft) in many headwater tributaries by the end of the nineteenth century (Knox, 2001). This reduced the frequency of overbank flooding and led to lateral channel migration rates greater than 50 cm yr^{-1} (19.7 in yr^{-1}) from rapid channel bank erosion (Knox, 2001). Although in-channel sources of suspended sediment dominate in the Wildcat Slough watershed and similar headwater tributaries in the Driftless Zone, the processes that led to them do not. Evidence for rapid soil erosion and floodplain deposition has not been observed in headwater tributaries in central Illinois. Also, channel migration in the Wildcat's watershed has not been witnessed at the rates recorded in the Driftless Zone.

Although historical land changes are similar in the Wildcat Slough watershed, the South Amana sub-watershed, and Driftless Zone, each region has had distinctly different sedimentological responses to change. The low-relief Wildcat Slough watershed shows no present or historical evidence of sediment contribution from the uplands to the channel. In contrast, the Driftless Zone shows evidence for dramatic upland erosion in the past, but channel bank aggradation has since caused a hydraulic response leading to almost exclusive sediment contributions from the banks. In the South Amana sub-watershed, both channel and upland contributions to the suspended load are observed.

Implications for management. Nutrient levels in central Illinois rivers exceed many EPA standards and it is often assumed that these nutrients are adsorbed to sediments and travel with them into the channels. Many best management practices (BMPs) aim to reduce sediment transport from fertilized and tilled farms by vegetating channel banks and adding levees at the tops of channelized banks. Results from this study suggest that these practices are succeeding in preventing sediment from directly entering the channels. However, since nutrient levels remain high, then BMPs should seek to prevent nutrient transport from alternative pathways such as dissolved nutrient export via tile drains or sediment transport from areas adjacent to meandering river reaches. By preventing fertilization near areas where channel migration is common, and replacing these fertilized areas with grass filter strips (eg. Gitau et al., 2005, Novotny, 2003, and Eghball et al., 2000), nutrients will not be introduced to the river by natural channel change or flooding.

CONCLUSION

In this study, the relative contributions of fine sediment from six sources within an anthropogenically influenced watershed in the heavily farmed Midwest were calculated. The results indicate a strong disconnect in sediment routing from the uplands to the channel. By combining a historical channel change analysis with a qualitative and statistical investigation of fine sediment geochemistry, this study determined that upland farms and land adjacent to a channelized river in low-relief regions do not contribute to the fine sediment load in the river. Instead, the suspended load in these regions is influenced solely by banks, forests, and grasslands that likely only contribute sediment during active channel migration.

The results of this study also point to unique characteristics of low-gradient, intensely managed headwater drainage basins. Because there is little relief in the uplands, and the tops of channelized banks have elevated crests, sediment cannot be transported directly from the uplands to the channels like in the South Amana watershed. Instead, channel migration in unchannelized meandering reaches is the primary contributor of sediment to the suspended load. Since there is no evidence for rapid soil erosion or channel migration in response to land use change as is seen in the Driftless Zone, it is likely that bank erosion has been the dominant process leading to sediment input in central Illinois since settlement began.

This study provides suggestions for best management practices aiming to reduce nutrient inputs from fertilized fields to the channels. These goals can be achieved by preventing channel migration through farm fields, either by improving the shear strength of actively eroding banks with vegetation to prevent bank erosion, or by increasing the distance of fertilizer application near channel banks. The results also indicate a need to identify alternative routes of nutrient transport that does not include adsorption to sediment because nutrients continue to be an environmental issue, even though the suspended sediment supply in low-gradient agricultural watersheds is influenced by channel processes in meandering reaches.

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FIGURES

Figure 1. (A) The Wildcat Slough is located in East Central Illinois. (B) The drainage basin of the Wildcat Slough is outlined and colored by land use according to the legend in panel C. (C) Sampling locations of potential sediment sources (orange dots) and suspended.

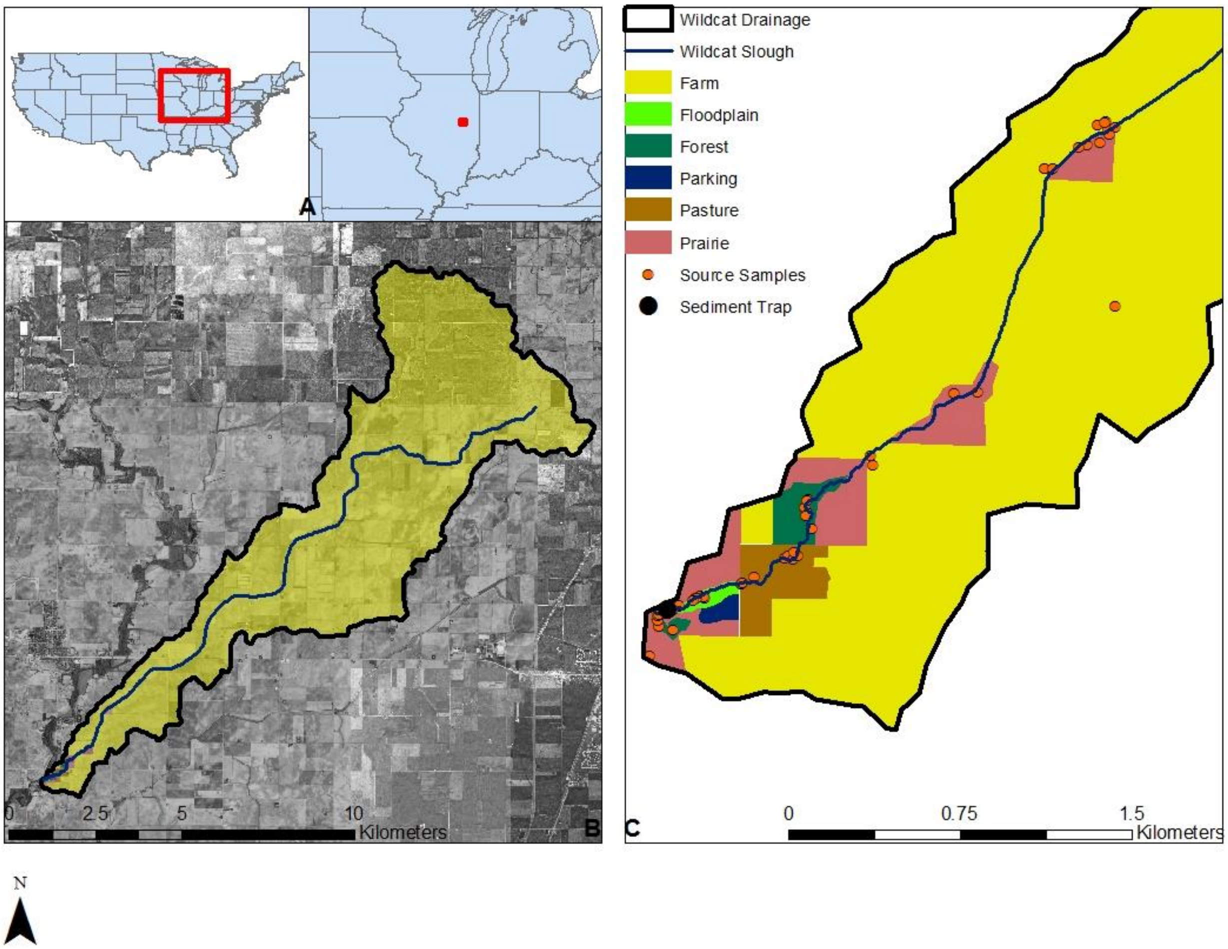


Figure 2. An example of the channelized portion of the Wildcat Slough (left) and large woody debris creates pools upstream (right).

Figure 3. Channel traces and length of the Wildcat Slough from 1940-2004. Traces were digitized in ArcMap10.1 after georectifying historical photographs to the most recent photographs available.

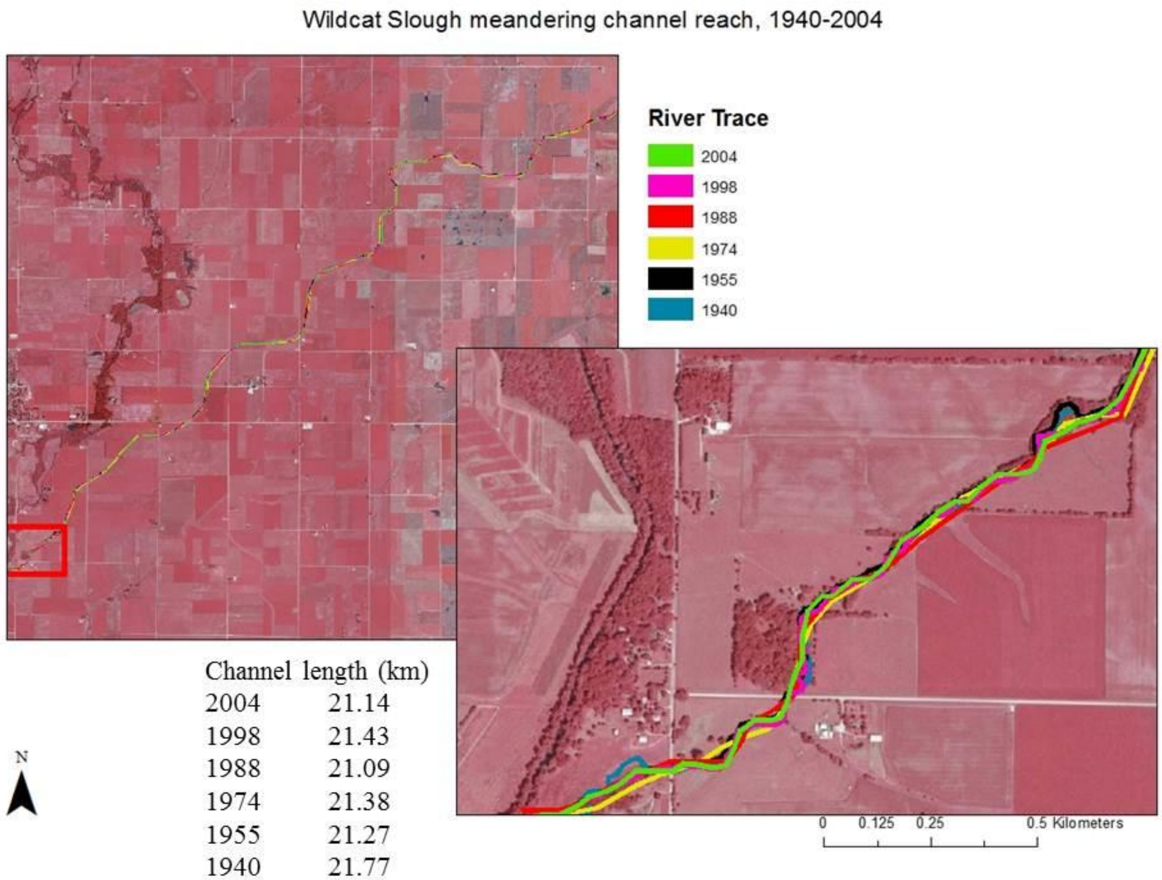


Figure 4. The sediment sampler, based on Phillips et al. (2000), and its position relative to the channel bed.

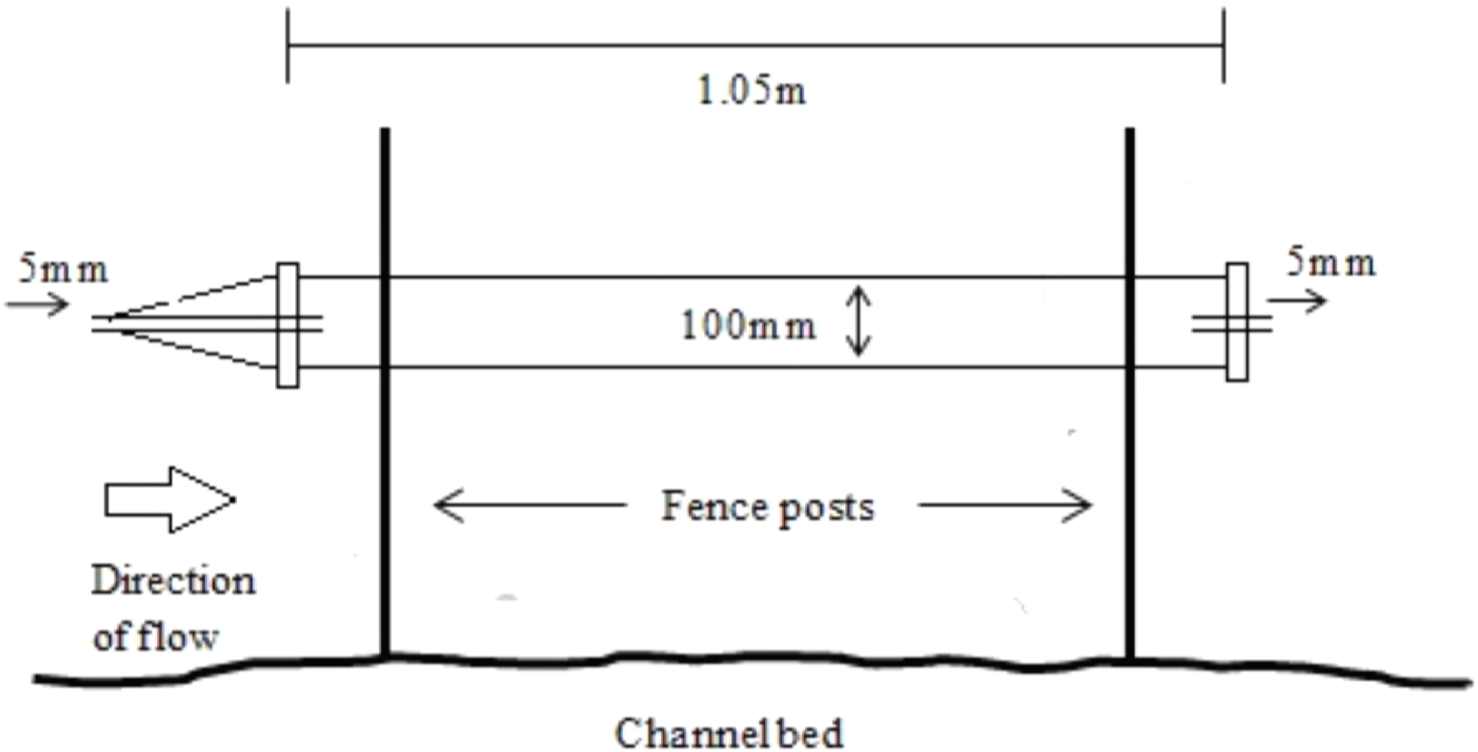


Figure 5. The soil series maps show the distribution of soils throughout the watershed (left) and from which series samples were collected (right).

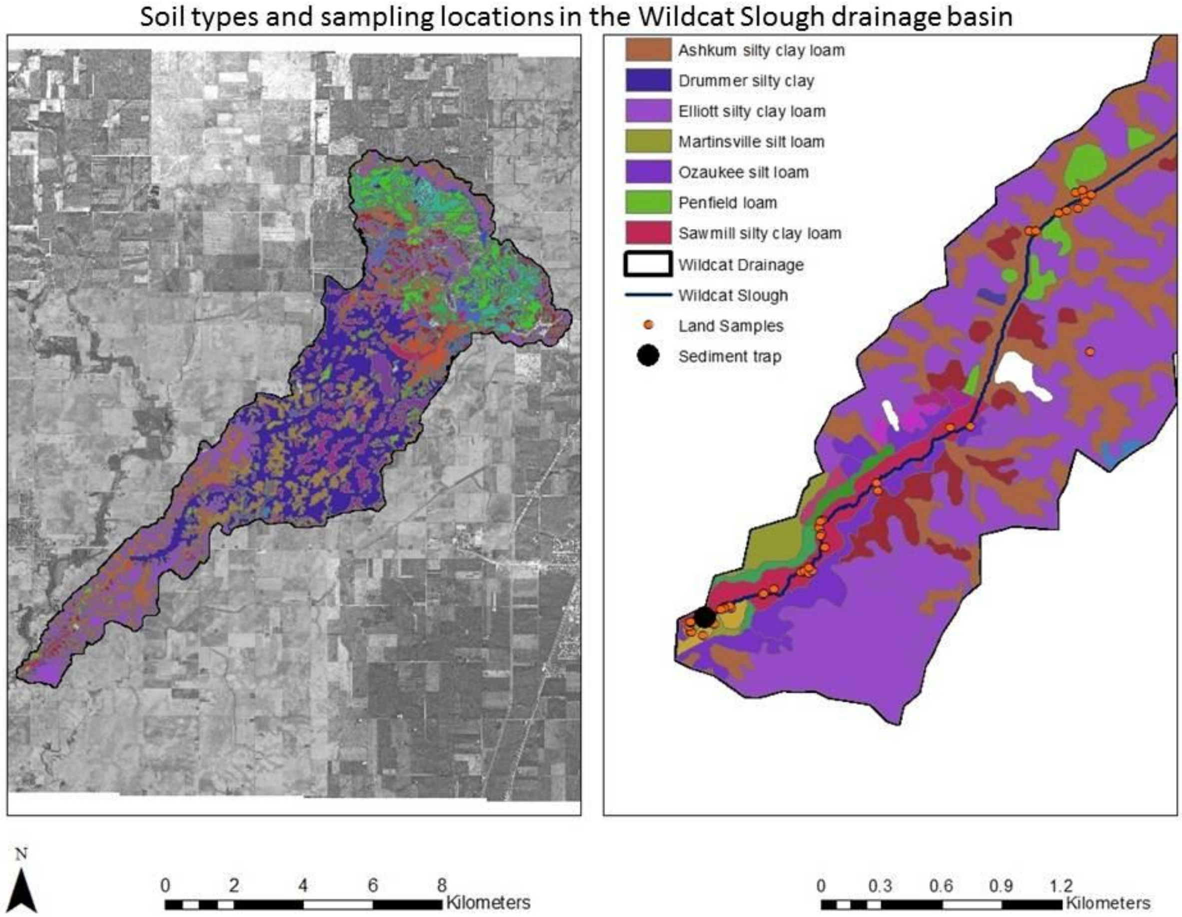


Figure 6. X-ray diffraction overlays after glycol and heated treatments for samples representing a (A) farm field, (B) floodplain, (C) forest, and (D) pasture in the Wildcat watershed.

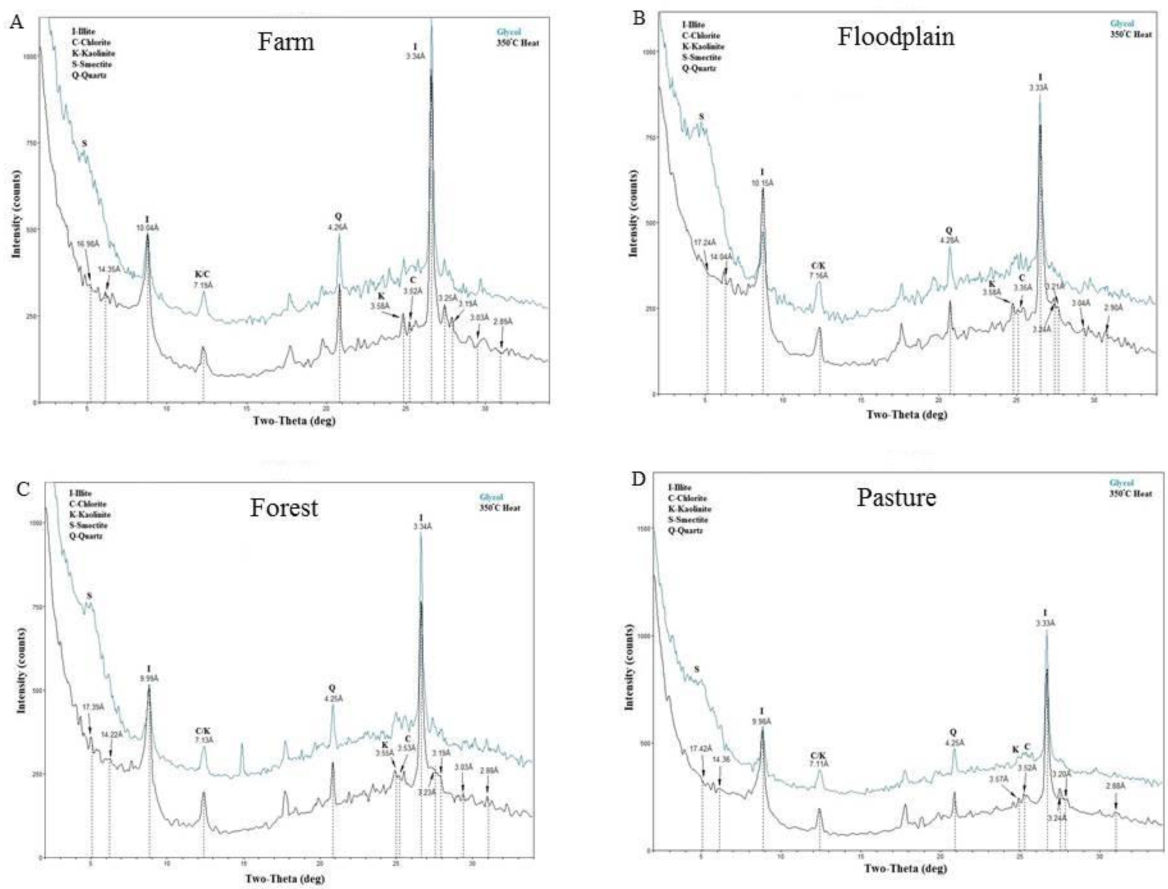


Figure 7. Pair plots of the five tracers output by the discriminant function, plus %C, for farm samples compared with the suspended sediment values.

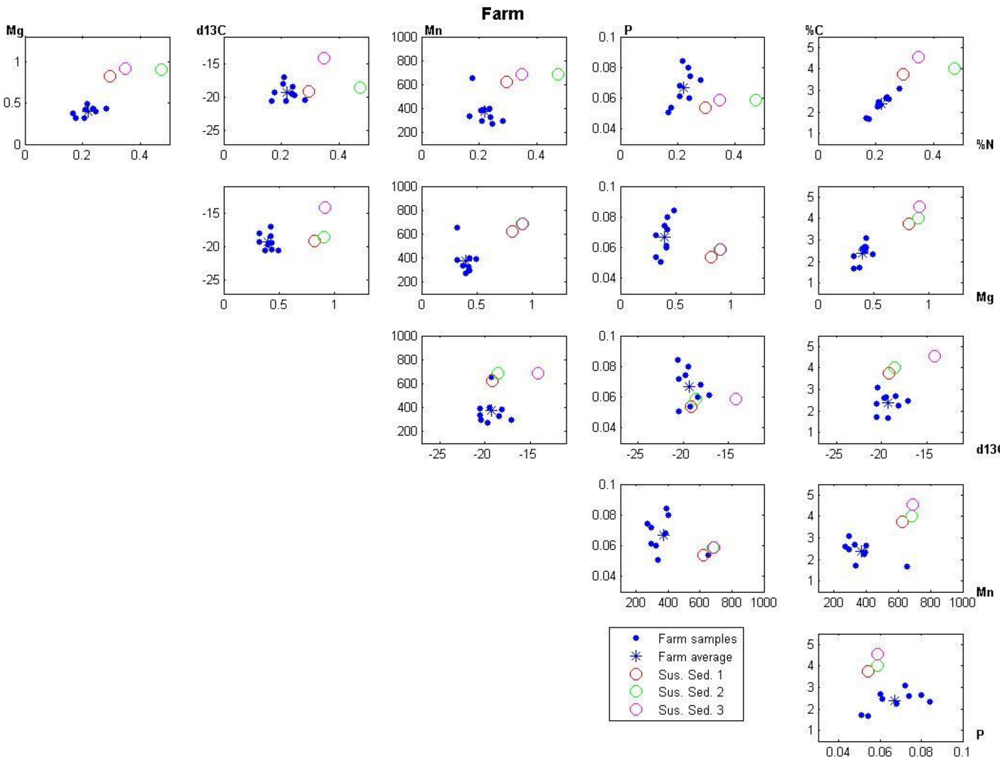


Figure 8. Pair plots of the five tracers output by the discriminant function, plus %C, for floodplain samples compared with the suspended sediment values.

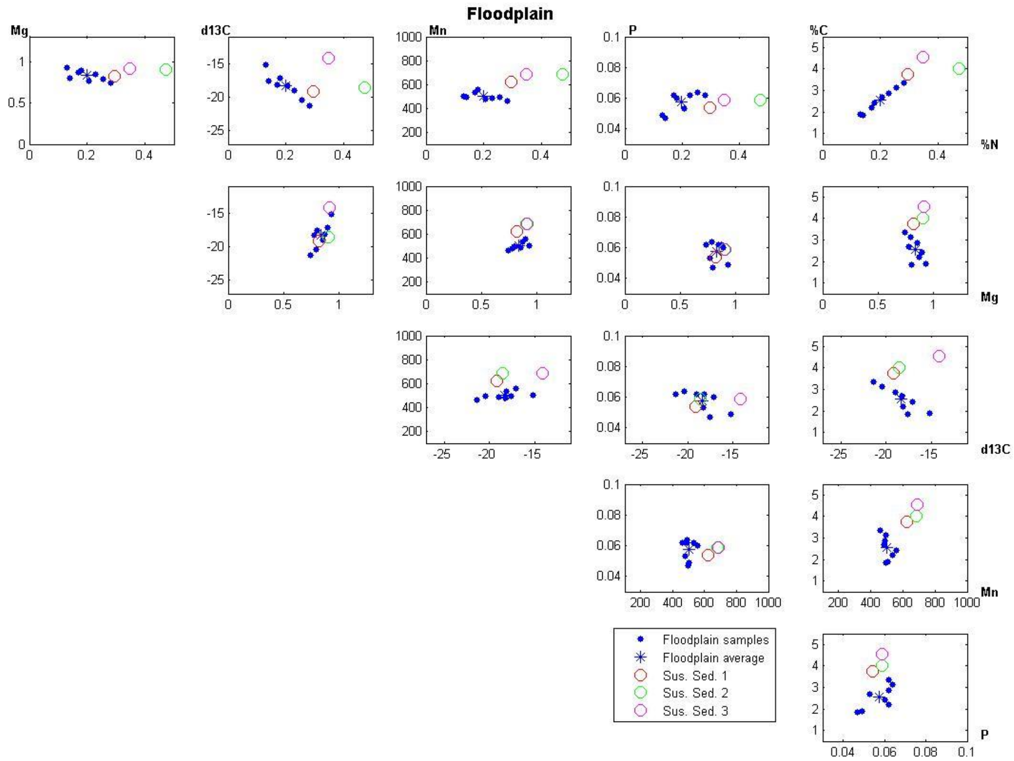


Figure 9. Pair plots of the five tracers output by the discriminant function, plus %C, for pasture samples compared with the suspended sediment values.

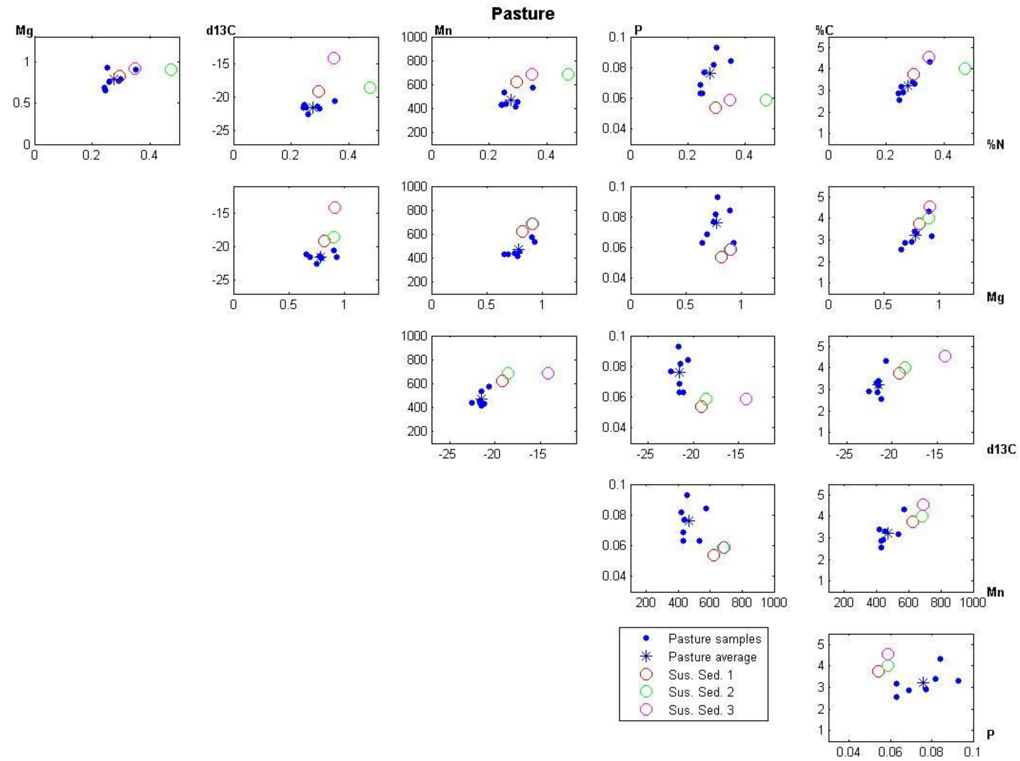


Figure 10. Pair plots of the five tracers output by the discriminant function, plus %C, for forest samples compared with the suspended sediment values.

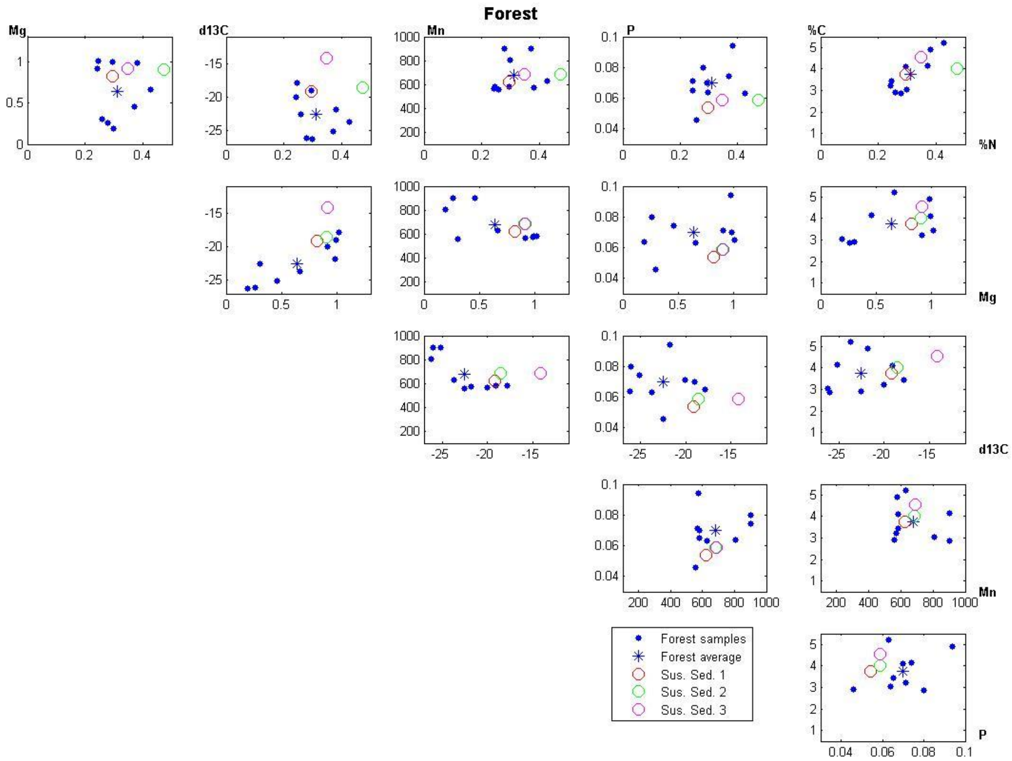


Figure 11. Pair plots of the five tracers output by the discriminant function, plus %C, for bank samples compared with the suspended sediment values.

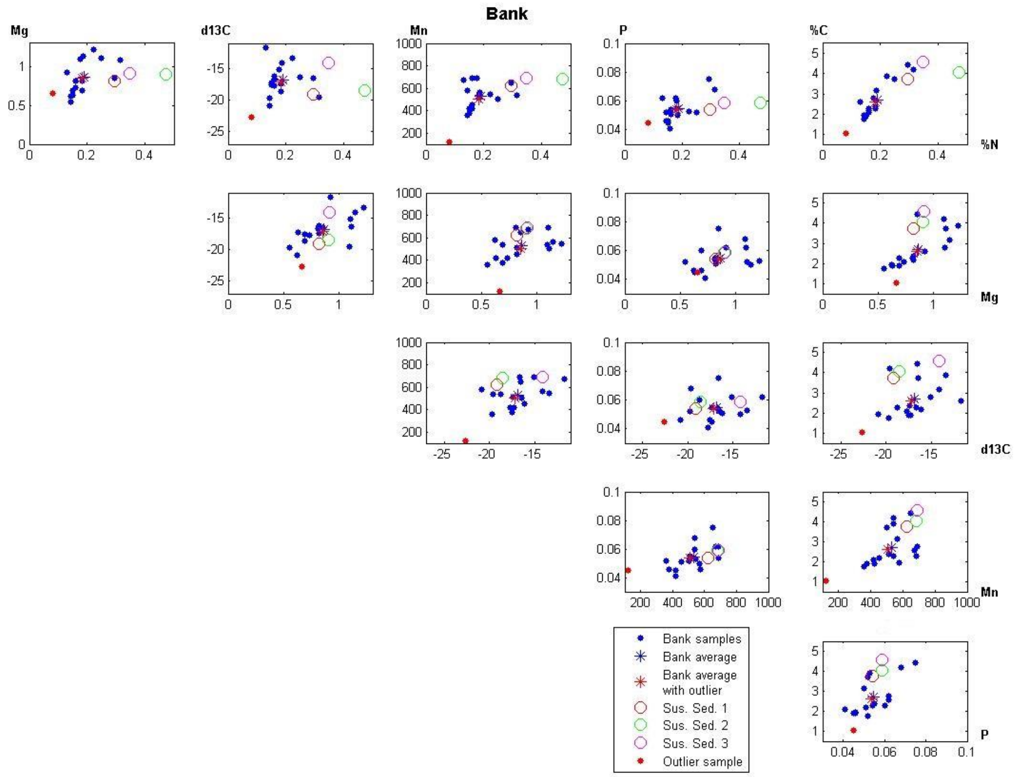
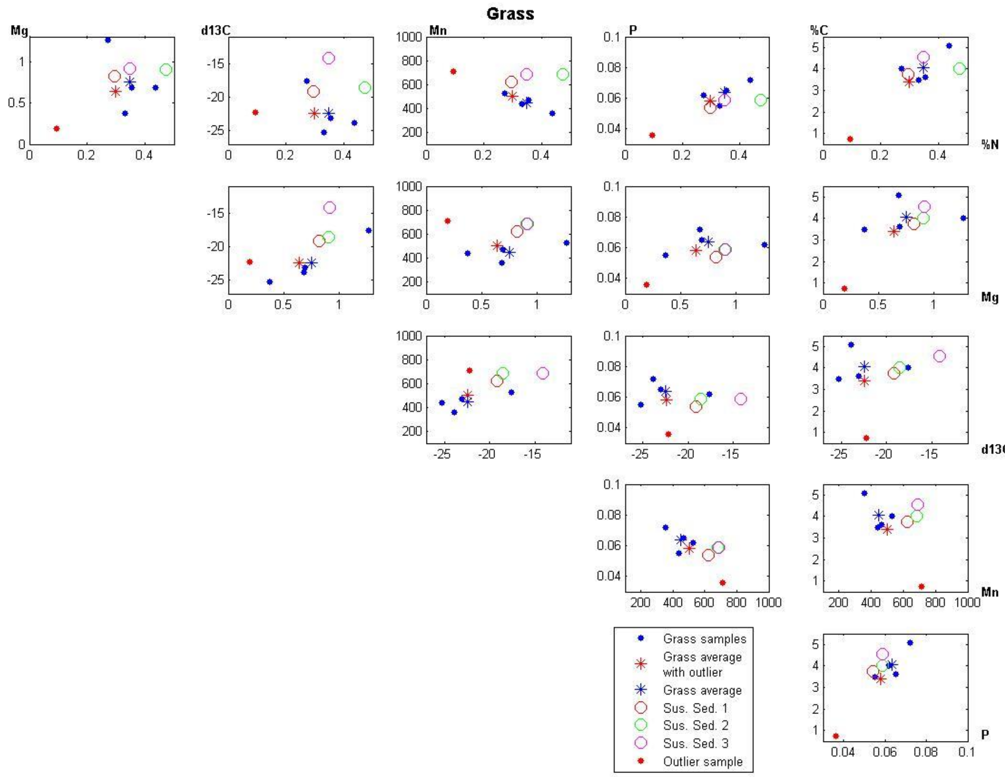


Figure 12. Pair plots of the five tracers output by the discriminant function, plus %C, for grassland samples compared with the suspended sediment values.



TABLES

Table 1. Area of each land type in the Wildcat Slough watershed.

Wildcat Slough		
Land type	**Area (km^2)**	**%**
Row Crop Agriculture	60.77	99.13
Forest	0.06	0.10
Floodplain	0.02	0.04
Grassland	0.32	0.52
Pasture	0.11	0.18
Parking lot	0.02	0.03
Total	61.30	100

Table 2. Dates and amount of precipitation from the events in which suspended sediment was collected. Precipitation data from CoCoRaHs station IL-CP-81. *denotes two events, $^+$denotes insufficient amount of sediment collected for all analyses.

Sample ID	Date	Amount of precipitation (cm)
FPSS 1-3	May 15-22	3.1*
FPSS 4$^+$	June 15	0.41
FPSS 5$^+$	July 21-22	0.79
FPSS 6, 7	October 22-November 2	5.84*

Table 3. Chemical compositions from tracers passing the Kruskal Wallis H test for each sample, as well as the source and soil series from which they were collected.

									Tracer											
Sample ID	Al (%)	Ca (%)	% C	δ13C	C/N	Cr (ppm)	Fe (%)	Mg (%)	Mn (ppm)	Na (%)	Ni (ppm)	%N	δ15N	P (%)	Sc (ppm)	Sr (ppm)	V (ppm)	Y (ppm)	Source	Soil Series
ShBank-1	2.06	0.95	1.91	-17.26	12.82	25	1.88	0.63	421	0.023	15	0.15	5.63	0.045	4	19	38	11	Bank	Sawmill silty clay loam
FpBank-3	2.16	1.56	2.17	-16.15	13.48	26	1.98	0.82	455	0.026	15	0.16	6.17	0.051	4	21	39	11	Bank	Sawmill silty clay loam
FpBank-1	2.06	1.7	2.37	-17.35	13.07	24	1.9	0.82	510	0.027	16	0.18	6.23	0.055	4	22	37	11	Bank	Sawmill silty clay loam
McBank-1	2.05	3.23	3.73	-16.43	14.97	24	1.91	1.11	501	0.028	14	0.25	6.05	0.052	4	29	36	11	Bank	Ashkum silty clay loam
McBank-3	2.1	2.63	4.19	-19.59	13.33	23	2.11	1.09	540	0.026	18	0.31	5.85	0.068	4	25	38	10	Bank	Ashkum silty clay loam
ShBank-3	2.07	0.96	1.90	-17.52	12.65	24	2.02	0.69	376	0.024	17	0.15	5.14	0.046	4	19	39	11	Bank	Sawmill silty clay loam
BanBank-1	2.2	1.83	2.59	-11.72	19.87	24	2.37	0.92	672	0.025	19	0.13	6.21	0.062	4	21	42	11	Bank	Sawmill silty clay loam
FpBank-5	2.39	0.64	1.75	-19.72	12.20	26	2.21	0.55	358	0.027	17	0.14	5.01	0.052	5	19	44	12	Bank	Sawmill silty clay loam
FpBank-7	2.1	1.1	2.27	-18.70	12.55	23	2.19	0.69	540	0.024	18	0.18	6.99	0.06	4	21	41	10	Bank	Sawmill silty clay loam
McBank-5	2.55	0.49	1.05	-22.64	13.04	35	2.35	0.66	123	0.025	22	0.08	-0.32	0.045	7	20	52	14	Bank	Ashkum silty clay loam
McBank-7	1.79	2.28	2.77	-15.10	15.71	21	2.15	1.1	687	0.023	17	0.18	7.19	0.062	3	22	34	10	Bank	Ashkum silty clay loam
FpBank-9	2.11	1.35	2.08	-17.69	13.06	23	1.88	0.73	418	0.03	13	0.16	4.76	0.041	4	19	38	9	Bank	Sawmill silty clay loam
McBank-9	2.2	3.94	3.16	-14.13	17.07	23	1.98	1.14	566	0.032	16	0.18	7.91	0.05	3	31	36	9	Bank	Ashkum silty clay loam
BanBank-3	2.31	1.88	2.29	-16.63	14.37	25	2.11	0.81	686	0.032	15	0.16	6.81	0.054	4	25	41	10	Bank	Sawmill silty clay loam
ShBank-5	2.59	0.66	1.94	-20.82	13.38	30	2.34	0.62	576	0.029	18	0.14	5.50	0.046	4	20	40	12	Bank	Sawmill silty clay loam
McBank-11	2.19	4.4	3.89	-13.40	17.47	23	2.03	1.22	542	0.032	15	0.22	7.27	0.053	4	31	34	9	Bank	Ashkum silty clay loam
McBank-13	2.31	4.35	4.45	-16.55	15.19	24	2.34	0.85	649	0.029	17	0.29	6.39	0.075	4	37	37	10	Bank	Ashkum silty clay loam
FpOak-1	1.07	0.3	3.05	-26.21	10.25	15	1.08	0.19	807	0.02	10	0.30	8.31	0.064	2	15	25	9	Forest	Sawmill silty clay loam
FpOak-3	1.28	0.38	2.87	-26.05	10.31	15	1.36	0.26	904	0.019	12	0.28	6.40	0.08	2	15	29	9	Forest	Sawmill silty clay loam
BanFor-1	1.92	2.61	4.11	-19.05	14.02	22	2	0.99	582	0.024	17	0.29	6.38	0.07	4	24	34	9	Forest	Sawmill silty clay loam
McFor-1	1.73	0.31	2.89	-22.51	11.26	19	1.6	0.3	558	0.019	13	0.26	4.18	0.046	2	14	35	9	Forest	Sawmill silty clay loam
BanFor-3	0.99	1.19	5.22	-23.73	12.27	13	1.5	0.66	629	0.02	10	0.43	3.54	0.063	2	13	24	7	Forest	Sawmill silty clay loam
BanFor-5	2.09	2.6	3.46	-17.83	14.16	23	1.98	1.01	580	0.027	15	0.24	6.42	0.065	4	24	37	10	Forest	Sawmill silty clay loam
BanFor-7	2.27	2.51	4.90	-21.78	12.86	25	2.1	0.98	576	0.032	16	0.38	6.34	0.094	4	27	40	10	Forest	Sawmill silty clay loam
BanFor-9	2.16	0.69	4.13	-25.14	11.16	25	2.08	0.46	900	0.029	16	0.37	5.49	0.074	3	18	40	11	Forest	Sawmill silty clay loam
BanFor-11	2.05	2.79	3.22	-20.04	13.30	23	2.19	0.91	569	0.025	16	0.24	6.96	0.071	4	27	36	10	Forest	Sawmill silty clay loam
FpFIP-1	2.41	1.26	3.35	-21.33	11.97	29	2.1	0.74	459	0.025	20	0.28	7.08	0.062	5	21	42	11	Floodplain	Sawmill silty clay loam
FpFIP-3	2.4	1.29	3.13	-20.40	12.33	29	2.15	0.79	492	0.027	19	0.25	6.22	0.064	5	21	42	12	Floodplain	Sawmill silty clay loam
FpFIP-5	1.95	1.57	2.69	-18.24	12.97	22	1.94	0.77	479	0.024	16	0.21	6.89	0.053	4	20	36	10	Floodplain	Sawmill silty clay loam
FpFIP-7	2.13	1.77	2.87	-18.95	12.61	23	2.09	0.85	490	0.025	16	0.23	6.70	0.062	4	21	39	10	Floodplain	Sawmill silty clay loam
FpFIP-9	2.43	1.62	2.40	-17.10	13.36	27	2.29	0.89	556	0.032	18	0.18	6.63	0.06	4	22	44	11	Floodplain	Sawmill silty clay loam
FpFIP-11	2.52	1.66	1.91	-15.15	14.67	28	2.29	0.93	505	0.033	18	0.13	7.30	0.049	4	23	44	11	Floodplain	Sawmill silty clay loam
FpFIP-13	2.43	1.04	1.87	-17.53	13.37	27	2.44	0.8	496	0.026	19	0.14	7.73	0.047	4	23	45	12	Floodplain	Sawmill silty clay loam
FpFIP-15	2.06	1.8	2.22	-18.10	13.07	23	2.17	0.87	535	0.022	16	0.17	5.99	0.062	4	22	36	11	Floodplain	Sawmill silty clay loam
FpPr-1	1.22	0.17	0.75	-22.21	8.04	16	1.26	0.19	712	0.02	9	0.09	1.20	0.036	2	14	30	8	Grassland	Martinsville silt loam
McG-1	1.86	0.94	5.09	-23.85	11.67	22	1.9	0.68	356	0.021	16	0.44	2.81	0.072	3	15	35	10	Grassland	Martinsville silt loam
McG-3	2.38	3.27	4.03	-17.60	14.83	26	2.29	1.26	529	0.031	18	0.27	5.69	0.062	4	37	42	10	Grassland	Martinsville silt loam
BanG-1	2.29	1.28	3.62	-23.07	10.29	25	1.99	0.69	467	0.03	15	0.35	5.59	0.065	4	19	40	10	Grassland	Ozaukee silt loam
BanG-3	1.72	0.47	3.51	-25.26	10.65	20	1.66	0.37	438	0.021	11	0.33	5.51	0.055	3	16	33	9	Grassland	Ozaukee silt loam
McFF-1	2.29	0.49	2.45	-17.09	11.78	28	1.86	0.42	292	0.026	14	0.21	7.52	0.061	5	20	42	12	Farm field	Ashkum silty clay loam
McFF-3	2.17	0.6	2.64	-19.44	11.19	23	1.92	0.43	400	0.021	15	0.24	8.05	0.08	4	18	42	11	Farm field	Ozaukee silt loam
McFF-5	1.77	0.38	2.23	-18.06	10.88	20	1.64	0.32	385	0.021	13	0.21	6.03	0.068	3	15	36	10	Farm field	Ashkum silty clay loam
McFF-7	1.91	0.32	1.69	-19.23	9.57	23	2.22	0.32	652	0.02	18	0.18	4.35	0.054	3	15	44	9	Farm field	Penfield loam
McFF-9	1.97	0.29	1.70	-20.51	10.20	23	1.73	0.37	336	0.023	14	0.17	3.56	0.051	3	13	37	9	Farm field	Ashkum silty clay loam
McFF-11	2.28	0.46	2.70	-18.41	11.32	26	1.88	0.42	326	0.025	14	0.24	7.44	0.06	4	17	41	10	Farm field	Ashkum silty clay loam
McFF-13	2.49	0.59	2.32	-20.55	10.79	29	2.16	0.49	391	0.027	16	0.22	5.34	0.084	4	19	48	12	Farm field	Ashkum silty clay loam
McFF-15	2.08	0.41	3.10	-20.47	11.09	24	1.97	0.43	293	0.021	14	0.28	7.58	0.072	4	17	38	10	Farm field	Ashkum silty clay loam
McFF-17	2.06	0.46	2.61	-19.71	10.69	24	1.86	0.4	270	0.022	13	0.24	7.63	0.074	4	18	39	11	Farm field	Ashkum silty clay loam
ShPa-1	2.03	1.35	2.89	-22.51	11.26	25	1.85	0.75	438	0.024	15	0.26	4.18	0.077	4	20	36	10	Pasture	Sawmill silty clay loam
ShPa-3	1.89	1.41	3.41	-21.48	11.77	21	1.88	0.77	418	0.021	15	0.29	7.80	0.082	3	19	34	9	Pasture	Sawmill silty clay loam
ShPa-5	1.91	1.1	2.85	-21.53	11.77	21	1.84	0.69	431	0.022	15	0.24	7.30	0.069	3	17	35	9	Pasture	Sawmill silty clay loam
ShPa-7	2	1.16	2.57	-21.13	10.51	22	1.85	0.65	431	0.024	14	0.24	8.54	0.063	3	18	36	9	Pasture	Sawmill silty clay loam
ShPa-9	2.11	2.02	4.35	-20.61	12.45	24	1.96	0.9	573	0.028	15	0.35	6.77	0.084	3	21	37	10	Pasture	Sawmill silty clay loam
ShPa-11	2.09	2.28	3.16	-21.51	12.63	24	2.17	0.93	534	0.023	17	0.25	7.38	0.063	4	24	36	10	Pasture	Sawmill silty clay loam
ShPa-13	1.76	1.75	3.31	-21.70	11.06	20	1.91	0.79	452	0.022	14	0.30	9.12	0.093	3	22	31	10	Pasture	Sawmill silty clay loam
FPSS-1	1.88	1.96	3.74	-19.14	12.68	24	2.08	0.82	624	0.029	60	0.30	6.46	0.054	3	24	36	9	Suspended Sediment	
FPSS-2	2.04	1.96	4.04	-18.54	8.56	25	2.26	0.9	682	0.029	24	0.47	6.47	0.059	3	24	39	10	Suspended Sediment	
FPSS-3	2.11	2.04	4.57	-14.16	13.22	27	2.29	0.91	688	0.031	22	0.35	7.25	0.059	4	26	40	10	Suspended Sediment	

Table 4. Clay mineral percentages determined by X-ray diffraction.

Source	%Illite – smectite	%Illite	%Kaolinite + Chlorite	%Kaolinite	%Chlorite	Sum
Pasture	28.7%	60.4%	10.9%	5.0%	5.9%	100%
Farm	25.5%	62.8%	12.7%	6.7%	5.0%	100%
Floodplain	32.3%	54.6%	13.1%	6.4%	6.7%	100%
Forest	25.8%	63.8%	10.5%	4.8%	5.7%	100%

Table 5. Results of the Kruskal-Wallis H test. All values above the critical value (11.07) are able to differentiate between the sources.

Tracer	*H* value	Tracer	*H* value
C/N	29.05	Al	15.61
$\delta^{13}C$	27.63	Sc	13.86
%N	23.91	$\delta^{15}N$	13.30
Mn	22.84	Na	12.38
P	21.78	Cr	12.29
V	18.95	K	11.00
Mg	18.41	Co	10.86
Ca	18.32	La	8.41
Ni	17.58	Zn	8.06
%C	16.87	Ba	4.81
Sr	16.53	Ti	3.67
Y	16.16	Cu	2.54
Fe	15.80	Pb	1.18

Table 6. Output from the discriminant function analysis creating the composite fingerprint.

Step	Tracer(s) used	Cumulative %	Wilks' lambda	Sig.
1	%N	51.9	.451	.389
2	%N Mn	81.6	.239	.006
3	%N Mn Mg	95.3	.144	.000
4	%N Mn Mg $\delta^{13}C$	99.2	.076	.000
5	%N Mn Mg $\delta^{13}C$ P	100.0	.045	.000

Table 7. Results of the forward model showing the relative contribution of suspended sediment by each source type for three suspended sediment samples.

		Forest	Grassland	Floodplain	Pasture	Bank	Farm	Uncertainty
FPSS-1	Best answer	5%	35%	0%	0%	60%	0%	26.95%
	Range	0-15%	20-35%	0%	0%	60-70%	0%	-
FPSS-2	Best answer	50%	0%	0%	0%	50%	0%	49.27%
	Range	35-50%	0-5%	0%	0%	50-65%	0%	-
FPSS-3	Best answer	55%	0%	0%	0%	45%	0%	52.63%
	Range	40-55%	0-10%	0%	0%	45-55%	0%	-